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MEMORANDUM

From: Bill Jemison
To: Dr. Daniel Tam, ONR
Date: 4/19/2013

Subject: Progress Report –
ULI Q2: FY13 Progress Report (1/1/2013– 3/31/2013).

This document provides a progress report on the project "Advanced Digital Signal Processing for Hybrid Lidar" covering the period of 1/1/2013–3/31/2013.

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FY13 Q2 Progress Report: Chaotic LIDAR for Naval Applications

This document contains a **Progress Summary for FY13 Q2** and a **Short Work Statement for FY13 Q3**.

Progress Summary for FY13 Q2

A new hybrid lidar-radar technique based on frequency domain reflectometry has been identified and initial work to investigate it has begun. This technique has the potential to increase the unambiguous range of hybrid lidar-radar while maintaining reasonable range resolution. Proof-of-concept simulations and experiments have been performed which provide preliminary validation of the technique.

Background

Current CW ranging techniques for hybrid lidar-radar are able to provide high resolution ranging but are limited by a short unambiguous range. We have identified new ranging signal processing approach based on frequency-domain reflectometry that has the potential to significantly improve unambiguous ranging capability. The existing hybrid lidar-radar single-tone signal processing method is able to achieve errors of five centimeters or less, even in highly turbid environments [1]. The frequency of the tone should be selected to be at least 100 MHz in order to take advantage of the hybrid lidar-radar backscattering reduction; a 100MHz modulation frequency corresponds to an unambiguous range of 1.125 meters. Frequencies above 100 MHz will further reduce backscattering enhance range resolution, but these frequencies will also have correspondingly smaller unambiguous ranges. The new approach described here has the potential to provide much larger unambiguous ranges than the single-tone approach, while a hybrid design approach allows it to maintain comparable range resolution to the single-tone method. Once the proof-of-concept is demonstrated, there will be additional system trade-off studies that will need to be performed to ensure that the processing can be done in real time.

Approach

To overcome the unambiguous range limitation of the single-tone approach, we have adapted a technique from the fiber optic community known as frequency-domain reflectometry (FDR). This technique was originally developed in the 1980s for the purpose of characterizing fiber lasers [2,3]. In the decades since, FDR has seen extensive use as an inexpensive method of approximating the location of faults in long fiber optic cables [4-7]. Utilizing modulation bandwidths of several gigahertz, this method has been used by the fiber optics community to unambiguously identify faults over several kilometers of fiber optic cable with the fault range resolution on the order of 10 to 20 centimeters.
The key steps behind the FDR method will be briefly discussed. First, a stepped-frequency signal is transmitted into the channel, which contains N distinct frequencies. This signal reflects off objects in the channel and is collected by the receiver. The receiver measures the magnitude and phase of this return signal for all transmitted frequencies. This information is used to construct the frequency spectra for the current state of the channel, which encodes information about the distance to any objects currently in the receiver's field of view in the form of complex sinusoids. The inverse Fourier transform is taken to convert these complex sinusoids into sharp peaks in the time domain, indicating the time-of-flight

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required for the signal to reach each object in the channel. Finally, the time-of-flight information is converted into range data through knowledge of the speed of light in the medium.

Comparison to Single-Tone

Table 1 summarizes the ranging equations for both the FDR and hybrid lidar-radar single-tone methods. The FDR unambiguous range depends on the step-size Δf of the stepped-frequency signal, while the FDR resolution depends on the modulation bandwidth BW. For the single-tone approach, both unambiguous range and range resolution depend on the modulation frequency f_m, with the range resolution also depends on the precision of the phase measurement, $\delta\varphi_m$. For the single-tone approach, increasing the unambiguous range by decreasing the modulation frequency will consequently decrease the range resolution. In addition, decreasing the modulation frequency below 100 MHz will cause backscattering to significantly impact the system. In theory, if the phase is measured by a highly accurate device, the resolution of the single-tone method will also be highly accurate. On the other hand, the range resolution of the FDR method will always be limited by Fourier theory, no matter how precise the phase is measured. However, by transmitting many tones at different frequencies, the FDR method can achieve much larger unambiguous ranges than the single-tone method.

Table 1. Comparison of FDR and Single-Tone Equations

Method	Max. Unamb. Range (m)	Resolution (m)
FDR	$R_{max} = vt_{max} = \frac{v}{2\Delta f}$	$\delta R = \frac{\Delta R}{2} = \frac{v}{4BW}$
Single-tone	$R_{max} = \frac{\lambda}{2} = \frac{v}{2f_m}$	$\delta R = \frac{v}{2\pi f_m} * \delta\varphi_m$

Ranging Simulations

Simulations of the FDR approach were performed using the Underwater RangeFinder simulator produced by ATMOTOOLS for the Navy [8]. RangeFinder allows the user to specify transmitter and receiver parameters, object properties, and water channel optical properties. For practical considerations related to the underwater channel and to our current experimental laser set-up, we restrict simulations to a maximum bandwidth of 1.2 GHz and up to 1024 frequency steps. Furthermore, it does not make sense to attempt to use the same design parameters as the fiber optics community, as system performance in the underwater channel will degrade as both distance and turbidity increase. Three sets of simulations have been performed and will be discussed below. First, an FDR scenario was tested in a pure water (c=0) simulation to verify that the method's full unambiguous range could be used in the absence of scattering. Second, FDR performance was simulated in turbid water with several different attenuation coefficients to assess scattering effects and also for comparison to previous work. Finally, FDR resolution was assessed for close targets for comparison to the resolution of selected single-tones.

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Unambiguous Range Simulation in Pure Water

The purpose of the first simulation was to ensure that, in the absence of scattering effects, the target could be detected throughout the full unambiguous range of an FDR-based system. In this case, the system was designed with the parameters shown in Table 2, allowing the system to unambiguously detect objects almost 48 m away with a resolution of about 4.7 cm. Figure 1 illustrates the results of this simulation, along with the range calculated by a single-tone system operating at 160 MHz, which has an unambiguous range of approximately 70 cm. The ambiguity issue is further illustrated in Figure 2 for an object 10 m away from the system. This shows that the single-tone provides many possible locations (i.e. the range is ambiguous) for the object that are less than the true distance to the object, while the FDR approach provides one possible location at 10 m due to its significantly large unambiguous range. To summarize, in pure water, this FDR configuration described in Table 2 is able to accurately and unambiguously detect objects for ranges almost 70 times greater than that of a single-tone system operating at 160 MHz.

Table 2. FDR system parameters for simulations

Parameter	Value
Bandwidth	$1.2\ GHz$
Number of transform bins	1024
Frequency step size	$1.17\ MHz$
Max. Unamb. Range	$47.95\ m$
Resolution	$0.0469\ m$

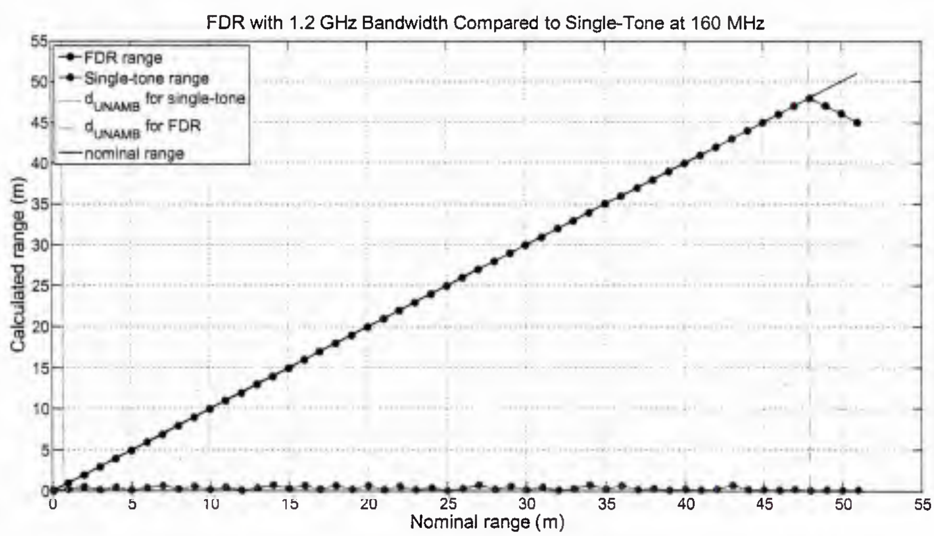

Figure 1. Pure water simulation (c=0). The FDR calculated range tracks the actual (simulated) range over its unambiguous range of 48meters. The single-tone approach has an unambiguous range that is much smaller, thus targets located beyond this range cannot be ranged unambiguously.

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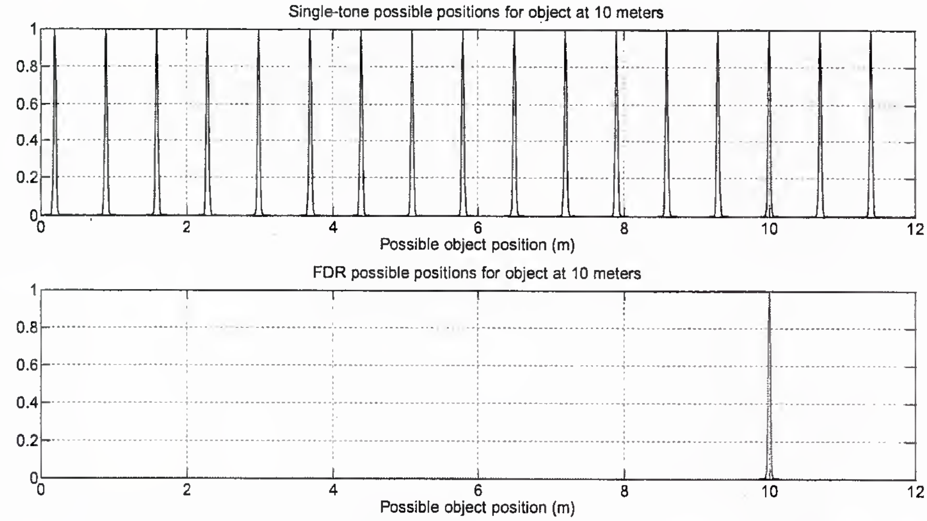

Figure 2. Range ambiguity for object at 10 meters in pure water simulation. The top plot shows that the single-tone hybrid lidar-radar range is ambiguous. The bottom plot shows that the FDR approach is unambiguous and detects the target at the proper range.

Ranging Simulations in Turbid Water

The second set of simulations varied the turbidity of the underwater channel to determine what fraction of the unambiguous range would remain useable in more practical scenarios. Results for four attenuation coefficients are plotted below in Figure 3. The FDR configuration for these plots was the same as that listed in Table 2. Although this configuration has a maximum unambiguous range of almost 48 meters, the method does not provide accurate range measurements out to that distance once it is applied to a turbid environment.

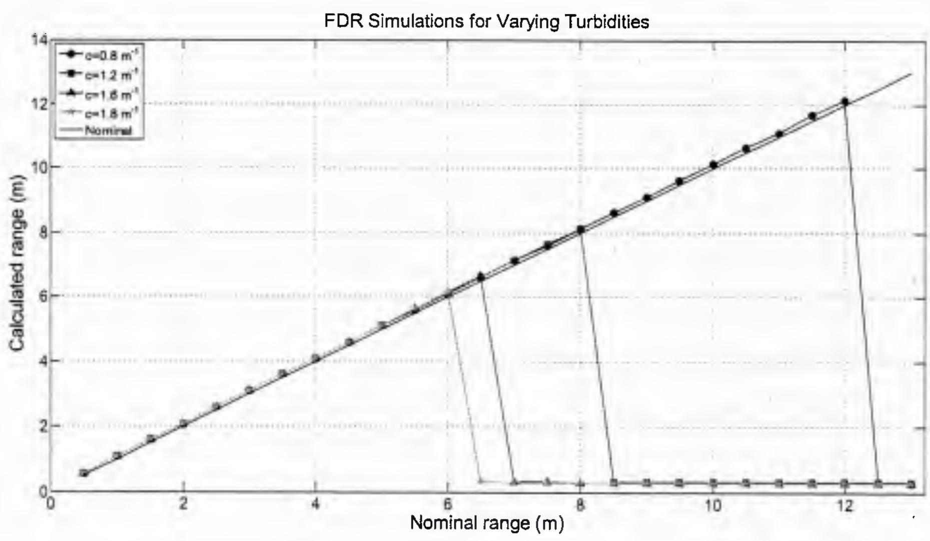

Figure 3. Simulation results at various turbidities. The

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Figure 3 shows the FDR performance does degrade with increasing turbidity. This is not unexpected as fewer photons are able to successfully make the round-trip from the system to the object and back with increasing turbidity. Figure 4 shows the relative amplitudes of returns from the target peak and the volumetric scattering peak. The amplitude of the volumetric scattering peak exceeds the amplitude of the target peak beyond approximately 7.2 m. This will cause an erroneous target range to be calculated. It may be possible to push this failure point out to farther ranges by utilizing more advanced signal processing.

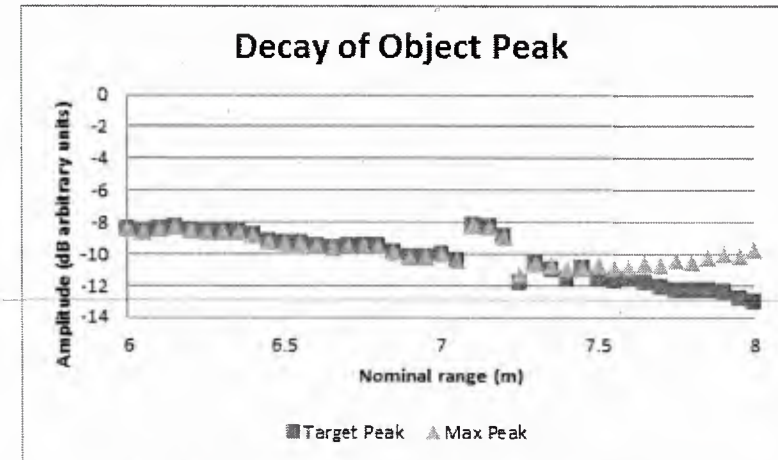

Figure 4. Decay of target peak amplitude as range increases

The performance of this FDR configuration will be compared to previous simulation results for the $c = 1.6\, m^{-1}$ scenario. Laux *et. al.* used the single- and dual-tone approaches to ambiguously range objects [1]. Perez et al developed a spatial filtering approach to help the single- and dual-tone approaches resist the effects of scattering [9,10]. In all three of these works, range ambiguity was manually removed through prior knowledge of object position in these experiments. Table 3 compares these previous methods to the new FDR approach, using the performance of a single-tone system at 20 MHz as a baseline for comparison. The single- and dual-tone approaches used by Laux *et. al.* improve the usable range by a factor of approximately two. Meanwhile, the spatial filtering approach of Perez *et. al.* is able to improve the ranging capability by a factor of approximately 2.6. The FDR approach provides an improvement of approximately 3.8 compared to the baseline, indicating that the use of the stepped-frequency waveform is able to better resist scattering effects than these other methods. The FDR approach requires additional dwell time for the multiple frequencies, and a more thorough system trade-off study is required.

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Table 3. Method comparison for simulation at $c = 1.6\ m^{-1}$

Scenario	Maximum Usable Range: Meters	Maximum Usable Range: Attenuation lengths	Relative improvement
Single-tone at 20 MHz	1.70	2.72	1.00
Single-tone at 160 MHz	3.50	5.60	2.06
Dual-tone at 160, 180 MHz	3.10	4.96	1.82
Single delay line canceler at 160 MHz	4.50	7.20	2.65
Double delay line canceler at 160 MHz	4.50	7.20	2.65
FDR (see Table 2)	6.50	10.40	3.82

Range Resolution Simulation

The third set of simulations aims to explore the resolution of the FDR method and to enhance it by creating a hybrid FDR/single-tone method. Figure 5 shows the ranges calculated by the FDR method (see Table 2) and four single-tones for an object whose position was varied from zero to three meters by steps of two centimeters. The single-tones track very closely to the nominal distance line throughout their respective unambiguous ranges. As the FDR method maps each range into a set of discrete bins, it can have errors up to half the bin size, approximately 4.69 cm in this case. Relative to the single-tone approach, this can be considered as a form of "quantization error" in the FDR method.

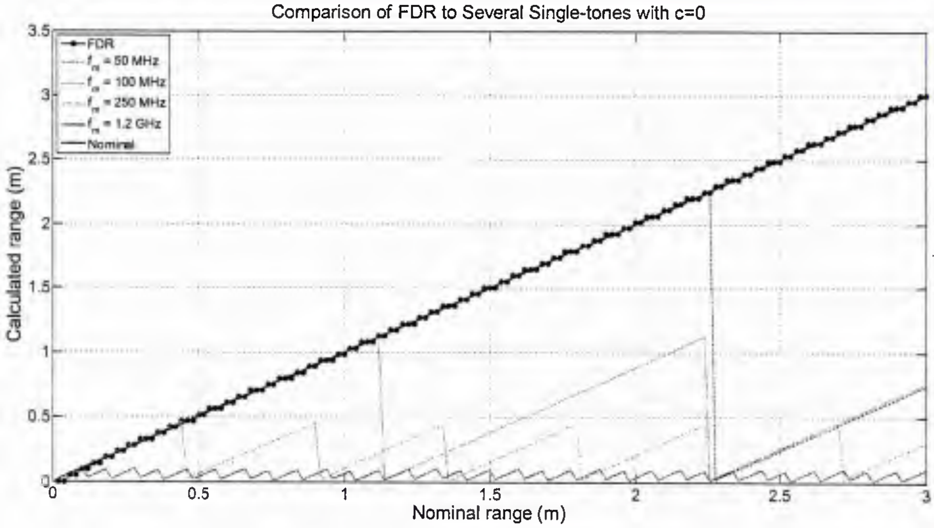

Figure 5. Comparison of FDR to single-tone for close range

The first five rows of Table 4 indicate the average and maximum errors after manually removing the ambiguity from the single-tone range measurements. Note that the maximum error for the FDR method is on the order of one-half of a Fourier transform bin. It can be seen that the single-tone average errors range from about 40% to 75% smaller than the average error of the FDR method, with the maximum

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error ranging from about 50% to 75% smaller than that of the FDR method. This serves as motivation to augment the FDR method such that it can achieve an error closer to that of the single-tone approach, while providing longer unambiguous range than the single-tone approach. As the FDR method consists of sending a series of frequencies, it is trivial to use one of these frequencies to perform single-tone ranging alongside the FDR method.

Table 4. Error comparison between ranging methods

Method	Average error (cm)	Maximum error (cm)
FDR	1.26	4.00
Single-tone at 50 MHz	0.73	1.69
Single-tone at 100 MHz	0.71	1.98
Single-tone at 250 MHz	0.58	1.85
Single-tone at 1.2 GHz	0.31	1.05
Hybrid method	0.61	2.92

The basic idea of the hybrid approach is to minimize the ranging error by adjusting the FDR range calculation. For simplification purposes, this hybrid method assumes that the FDR approach placed the range in the correct bin, but has accrued some quantization error as a result of this process. The FDR range measurement is compared to the range measurement of a single-tone, with the difference considered as a measurement of the quantization error. In principle, any frequency can be used for the single-tone as long as it is above 100 MHz so that backscattering effects are reduced. The final range calculation is adjusted by the calculated error value, as long as the adjustment would not push the range into a new FDR bin. In this way, the quantization effect of the FDR method is reduced, leading to a reduction in ranging error.

The reduction in error from applying the hybrid method is shown below in Figure 6. The FDR error is observed to oscillate, due to measurements being mapped to the closest bin. On the other hand, the single-tone error is a very smooth function, with some transient behavior for objects closer than about 0.5 m. The hybrid method, whose error is indicated with the circular markers, tends to follow the single-tone error curve, while also matching the FDR error in some cases where the FDR error was less than the single-tone error. It is clear that there are many points where the hybrid method erroneously kept the original FDR measurement. These points correspond exactly to the locations where the single-tone method "wrapped" around from its maximum unambiguous range to zero. This implies that the hybrid method requires some refinement to overcome this "wrapping" issue. Despite this issue, the hybrid method successfully reduces the ranging error compared to FDR alone, with the maximum error reduced by over 25% to 2.92 cm and the average error reduced by over 50% to 0.61 cm. Furthermore, this enhancement does not have any negative impact on the unambiguous range provided by the FDR method.

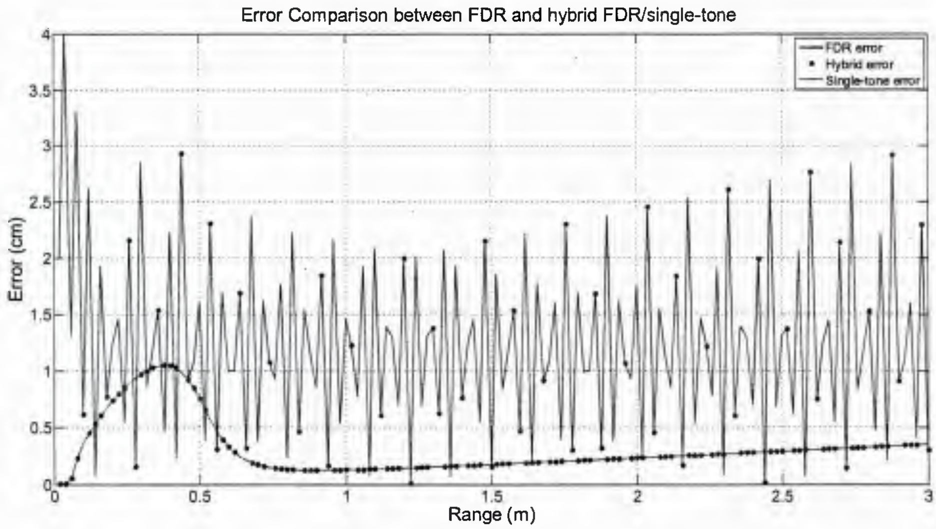

Figure 6. Error of hybrid method compared to each method by itself

Proof-of-Concept Experiment Results

A small proof-of-concept experiment has been performed using tap water in a one meter long water tank. The goals of this experiment were twofold. The first goal is to prove that the FDR approach could accurately range throughout the length of the tank. The second goal is to verify that the hybrid method will reduce the ranging error.

The experimental set-up is sketched below in Figure 7. For proof-of-concept purposes, a commercial vector network analyzer (VNWA) manufactured by SDR-Kits is used to generate the stepped frequency sweep. This device has a long dwell time of 1.33 milliseconds per frequency; it will be replaced in the future by a signal generator with shorter dwell time. The stepped frequency signal is provided at the RF modulation input of a Thorlabs diode fixture, which contains a 450 nm blue laser diode (OSRAM PL TB450). The modulated laser signal bounces off of a mirror that is suspended into the water tank and mounted on a translation stage. Due to logistics limitations of the current setup, we are only able to range through 70 cm of the tank. The return optical signal is focused down onto a Thorlabs DET10A detector, where it is converted into an electrical signal and sent to the receiver input of the VNWA. The VNWA performs a homodyne down-conversion on the return signal, and calculates the magnitude and phase of the return. This data is transmitted over USB to a PC running the VNWA software. Once the sweep has completed, the data is exported to custom MATLAB software that applies the FDR ranging algorithm to calculate the range to the object.

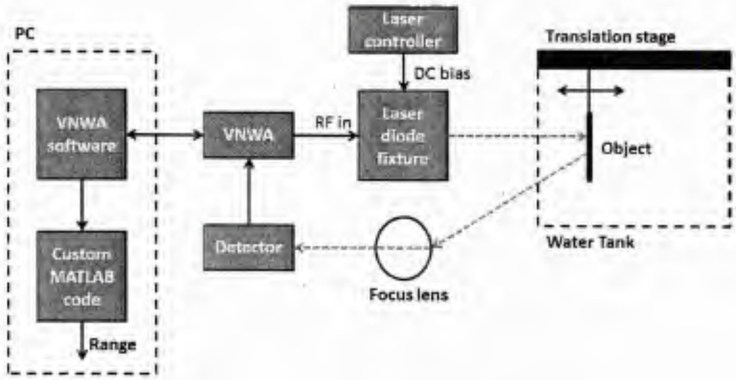

Figure 7. Proof-of-concept experimental set-up

The results of this proof-of-concept experiment are shown in Figure 8. Five measurements were made at each position, with the error bars showing the standard deviation. The FDR configuration was defined by the parameters of Table 2. These results indicate that the FDR method is able to successfully provide accurate range measurements throughout the usable length of the water tank. The quantization behavior of the FDR algorithm is clearly visible in the results. Additionally, data points that are close to the boundary between two bins have substantially larger errors, as some measurements placed these points into one bin while others placed them into a second bin. The hybrid FDR/single-tone method is applied to reduce the ranging error for a single-tone with frequency 175 MHz, with the error comparison shown in Figure 9. Note that the single-tone error is not as smooth as observed in the Rangefinder simulation of Figure 6; this is believed to be due in part to the quality of the phase measurements made by the VNWA. As with the simulation results, it is clear that further refinements are needed to optimize the performance of the hybrid method, although it is worth noting that most of the FDR points with high error have been corrected. Compared to FDR alone, the hybrid method reduces the maximum error by about 31% from 5.3 cm to 3.7 cm and also reduces the average error by nearly 30% from 1.65 cm to 1.15 cm, validating that the hybrid method can improve ranging accuracy in a real experiment.

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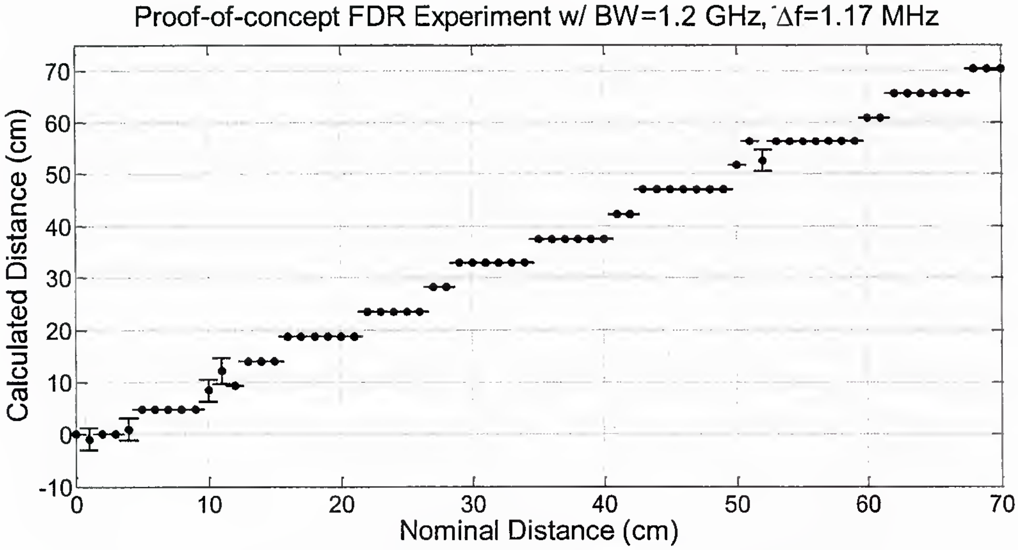

Figure 8. Proof-of-concept FDR ranging experiment in pure water

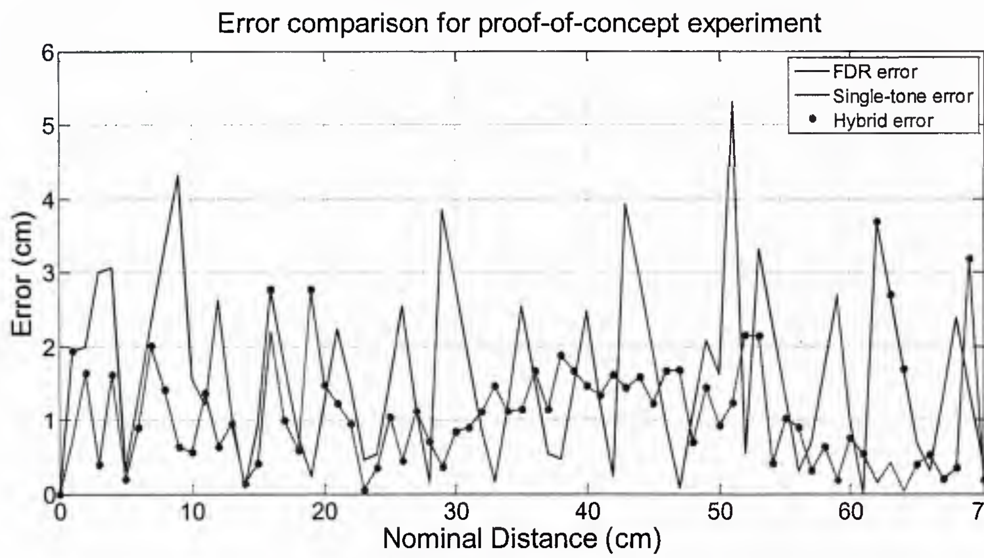

Figure 9. Error comparison for proof-of-concept experiment

Conclusions

A new ranging methodology for hybrid lidar-radar ranging systems has been identified and is currently being explored. The method borrows from the frequency-domain reflectometry technique used by the fiber optic community to detect faults in long fiber optic cables. This technique provides unambiguous range many times larger than that achievable with the single-tone ranging approach, resolving a critical drawback to the single-tone ranging approach. Due to the mathematical foundation of the frequency-domain reflectometry method, it may have larger range errors than a single-tone approach. This has motivated the development of a hybrid frequency-domain reflectometry/single-tone ranging approach, in which the frequency-domain reflectometry method provides large unambiguous range while the single-

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tone approach reduces the ranging error. Simulation and proof-of-concept experimental results have been demonstrated illustrating the improvements achievable through this hybrid approach. Average error was reduced by almost 50% in simulation, with a reduction of 30% in the proof-of-concept experiment. Future research goals include refinement of the hybrid method, small- and large-scale experiments at varying turbidities with higher quality, and exploration of the use of spatial filtering or other methods to further enhance the ranging performance of the hybrid method. The FDR approach requires additional dwell time and this must be incorporated into more thorough system trade-offs.

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<u>Short Work Statement for FY12 Q3</u>

The FDR approach will continue to be explored through both simulation and experimentation. We will also initiate another new hybrid lidar-radar signal processing technique for backscatter reduction based on blind signal separation.

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